Application Note

TI 15.4-Stack Software

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ABSTRACT

This TI 15.4 software application note describes the overall TI 15.4 stack software, which is a rough overview of the deliverables that TI provides for developers. For more detailed information, see the Developers guide that can be downloaded from the following URL: https://www.ti.com/tool/SIMPLELINK-LOWPOWER-SDK.

Table of Contents

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1 Overview

The TI 15.4-Stack is a software platform to implement an IEEE 802.15.4 based hardware access layer (PHY + MAC) on the SimpleLink™-MCU platform. It empowers its user to create a robust and secure star-network based on the IEEE802.15.4 standard. The stack is easy to configure and adapts to a diverse range of application requirements. TI provides the SDK, containing the stack as well as a detailed description and a set of out-of-the-box examples.

The TI 15.4 Stack includes different PHYs to comply to worldwide certification standards and to adapt different application requirements.

TI 15.4 stack implementation adapts to IEEE802.15.4e for industrial applications as well as 802.15.4g for smart utility networks (SUN). The stack includes an implementation for frequency hopping based on Wi-SUN™ implementation.

Moreover, the stack supports different modes and several security features, such as AES128 packet encryption.

Component	Version
TI-15.4-stack release	6.10.00.x
Distribution	Included in SDK (recent release 7.10.00.98)
IDE support	CCS V12.3 for Windows, Linux and macOS
Compiler support	TI Arm® Clang Compiler tools: 2.1.2.LTS, EWARM-9.32.1
RTOS Support	FreeRTOS V10.2.1
Recommended development kits	2x LP-CC1352P7-1 +Linux PC for OAD
Supported Devices:	**SUB1G**: CC1311P3, CC1311R3, CC1312R, CC1312R7, CC1312PSIP, CC1314R10 **2.4GHZ Devices:** CC2642R, CC2642R-Q1, CC2651P3, CC2651R3, CC2652P, CC2652P7, CC2652R, CC2652RB, CC2652RSIP, CC2652PSIP, CC2651RSIPA, CC2674R10, CC2674P10 **Dual Band Devices:** CC1352P, CC1352P7, CC1352R, CC1354P10, CC1354R10

1.1 Acronyms

Table 1-1. Acronyms Used in This Document

Acronym	Description
DH1CF	Direct Hash Channel Function
MAC	Media Access Controller
NPI	Network processor interface
OAD	Over the Air
OSI	Open System Interconnect
PAN	Personal Area Network
PHY	Physical Layer
RTOS	Real Time Operating system
SDK	Software Development KIT
SRAM	Static Random Access memory
SUN	Smart Utility Networks

1.2 Regulatory Compliance

1.2.1 TI 15.4 Stack

The TI 15.4 stack is royalty-free and does not require license or certification.

However, the software platform implements the standards IEEE802.15.4e (industrial) and IEEE802.15.4g (smart utility networks) specification with the most recent updates. TI SysConfig tool supports the adaption to different regulatory bodies.

1.2.2 Regulatory Body

Various PHY and MAC configurations adapt to different regional regulatory compliance such as:

- FCC
- ARIB
- ETSI

Note that regional regulations may change at any time. The TI 15.4-Stack parameters can be changed to adapt to new regulations.

To simplify certification, the Simplelink SDK provides a 15.4 Test mode. Using this mode, the sensor starts to send back-to-back messages, which can be captured by a spectrum analyzer.

1.2.2.1 SUB 1

The stack offers the opportunity to change the minimum TX-Off time which is set to a default value of 2ms for ARIB and 100ms to adapt to ETSI regulation. With our series of P1 devices, the possibility to adjust transmit power between 0 and 20 db is offered. This helps to adapt to regulatory bodies and change transmit power without being forced to do changes.

1.2.2.1.1 ETSI

In order to be ETSI compliant 15.4 uses EN 300 220-1 compliant Listen before Talk method (polite spectrum access) to access the frequency for transmitting messages in Beacon and non Beacon mode. For more information, see Section 6.

1.2.2.1.2 ARIB

TI 15. 4 is compliant to ARIB STD-T108 Version 1. 3. To adapt to ARIB, it is possible to limit the tx-Duty cycle as well as the minimum tx-Off-Time. These values are set by default but can be adapted easily. For more information on how to adapt to ARIB, see the *ARIB Regulation Type* section in https://dev.ti.com/tirex/explore/node?node=A__AITUIbVTzCdD7w7KebQ-qA__com.ti.SIMPLELINK_CC13XX_CC26XX_SDK__BSEc4rl__LATEST

This duty cycle limitation supervises the TX time of a device and rejects data transmission as soon as it would violate utilization settings.

1.2.2.1.3 FCC

TI 15.4 stack is developed to be compliant to:

- FCC Title 47, Telecommunication Part 248, Code of Federal Regulations
- FCC Title 47, Telecommunication Part 247, CFR 15.247, Code of Federal Regulations

The FCC regulatory body allows higher transmission power when using frequency hopping. Information on how this is done in our stack, can be found in our *TI 15.4-Stack Frequency Hopping Mode FCC Compliance*.

1.3 Polite Spectrum Access Timing Parameters

TIs 15.4 Stack offers a polite spectrum access with the following timing parameters shown in Table 1-2.

Table 1-2. 15.4 Stack

Parameter	Limit	Applied Value	Notes
Minimum CCA interval	160 µs	160 µs	Minimum CCA listening period
Minimum deferral period	CCA interval	**unitBackoff Duration (1 ms + 8 symbol period)**	Minimum value of the deferral interval
Minimum unit of deferral period		**unitBackoff Duration (1 ms + 8 symbol period)**	Smallest interval between two adjacent deferral periods
Dead Time	<5 ms	CCA duration (< 160 µs)	Maximum time between the end of a listening interval and the start of a transmission

Table 1-2. 15.4 Stack (continued)

Parameter	Limit	Applied Value	Notes
Maximum Transmission Duration Ton Max	1 s	Determined by Application max payload size & data rate (for 1000 bytes @ 50 kbps = ~200 ms)	For a single Transmission
Maximum Transmission Duration Ton Max	4 s	Determined by Application max payload size and data rate with polling overhead (for 1000 bytes @ 50 kbps = ~250 ms)	For a Transmission dialogue or a polling sequence
Max Tcum_on over 1 hour	100 s / 1 h per 200 kHz spectrum	Determined by Application traffic	Maximum allowed Cumulative On Time over a 200 kHz portion of spectrum per hour
Minimum Toff_min on the same Operating Frequency	100 ms	100 ms	The minimum T-off time period where a specific transmitter shall remain off after a transmission on the same Operating Frequency

1.3.1 2.4 GHz

The TI PHY/MAC of the 2.4G frequency band is compliant and certified to be used in ZigBee. Certification Number: 74687RZB.001.

1.3.2 Coexistence

IEEE 802.15.4 stack and Wi-Fi Channels both use 2.4 GHz frequency bands. Using both protocols in one environment might cause issues. TI 15.4 stack offers a coexistence scheme that is described to ensure interference free Wi-Fi and 15.4 communication. More information on this can be found in the User's Guide section: *Wi-Fi Coexistence*: Wi-Fi Coexistence — SimpleLink™ CC13XX/CC26XX SDK TI 15.4-Stack User's Guide 5.20.00.00 documentation.

2 Reference Examples

Code Example	Description
Collector (SUB1G/2.4G)	The collector example creates a PAN-Coordinator device using TI 15.4-Stack
Collector Secure Managed (SUB1G/2.4G)	The example creates a PAN-Coordinator device using TI 15.4-Stack-based star network with secure commissioning
Sensor (SUB1G/2.4G)	The sensor example can be used to join the PAN network created with the Collector example
Sensor Secure Managed (SUB1G/2.4G)	The sensor example can be used to join the PAN network created with the Collector Secure managed example
Coprocessor	Demonstrates how to implement a MAC coprocessor device in a two-chip scenario. In this example, the TI 15.4-Stack runs on a SimpleLink device, which can be interfaced with any device using a serial interface.
Sensor OAD off-chip secure (2.4G/SUB1)	The Sensor OAD Off-chip example application demonstrates how to implement a sensor network using TI 15.4-Stack with off chip OAD configuration with AM335x and MAC- Coprocessor.
Sensor OAD on-chip secure (2.4G/SUB1)	The Sensor OAD on-chip example demonstrates how to implement a 15.4 network with on-chip OAD capabilities with AM335x and MAC- Coprocessor.
Sensor OAD on-chip persistent secure (2.4G/SUB1)	The Sensor on-chip persistence example demonstrates how OAD with AM335x and MAC coprocessor works with an persistent image along the application image.

2.1 Available Chipsets

Table 2-1 shows that TI offers several Simplelink devices with a various amount of Flash and SRAM memory.

Table 2-1. Devices With a Various Amount of Flash and SRAM Memory

Device	Flash (kB)	SRAM (kb)
CC13x1x3 or CC26x1x3	352	40
CC13x2x1 or CC26x2x1	352	80
CC13x2x7 or CC26x2x7	704	144
CC13x4x10 or CC26x4x10	1024	256

With different system Cores:

- For CC13x1 and CC26x1 devices the system core is Arm Cortex®-M4
- For CC13x2 and CC26x2 devices the system core is Arm Cortex-M4F
- For CC13x4 and CC2674 devices the system core is Arm Cortex-M33

In order to find the right chip, one should consider the amount of RAM and Flash that is required for our examples in different configurations. These values are estimated using examples from the Simplelink SDK. The memory allocation can be found in Table 2-2.

TI-SimpleLink devices with P-extension have in integrated Power Amplifier, which enable adaptable transmission power with up to 20 dbm.

These values are estimated using our examples and the maximum number of connected devices for a Coordinator set to 50. The values can be found in Table 2-2 as Flash or RAM in kB.

2.2 Flash and RAM Allocation

Table 2-2. Device|Example|Flash|RAM

CC1352	Collector	143 kB	14 kB
CC1352	Collector_2_4g	133 kB	13 kB
CC1352	Collector_sm	155 kB	16 kB
CC1352	Collector_2_4g_sm	145 kB	15 kB
CC1352	Coprocessor	137 kB	13 kB
CC1352	Sensor_2_4g	108 kB	12 kB
CC1352	Sensor	119 kB	13 kB
CC1352	Sensor_oad_offchip_2_4g_secure	268 kB	13 kB
CC1352	Sensor_oad_offchip_secure	278 kB	14 kB
CC1352	Sensor_oad_onchip_2_4g_secure	262 kB	12 kB
CC1352	Sensor_oad_onchip_persisten_2_4g_secure	246 kB	12 kB
CC1352	Sensor_oad_onchip_persistent_secure	256 kB	13 kB
CC1352	Sensor_oad_onchip_secure	273 kB	13 kB
CC1352	Sensor_sm_2_4g	220 kB	13 kB
CC1352	Sensor_sm	131 kB	14 kB

3 Software Block Diagram

The TI 15.4-Stack implements the MAC and PHY layer of the Simplelink devices and is implemented as shown in Figure 3-1.

The out-of-the-box examples provide applications using the TI 15.4-Stack. On top of the TI 15.4-Stack other features like security or OAD can be implemented as done in our examples.

More information regarding the software architecture can be found in the TI 15.4-Stack User's Guide within the Application overview section. TI 15.4-Stack is FreeRTOS POSIX compatible. TIs SDKs contain several examples running the TI 15.4 stack using FreeRTOS.

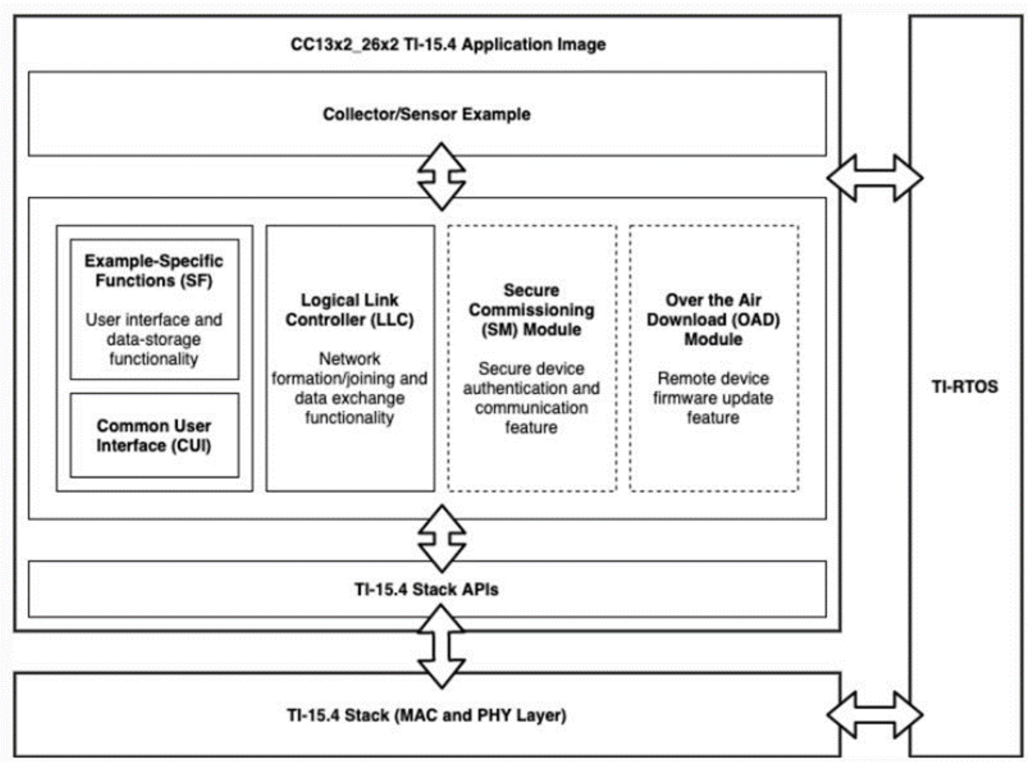

Figure 3-1. Software Block Diagram

4 Network Features

4.1 15.4 Supported PHYS

The 15.4 stack out of the box supports several PHYs covering multiple data rates and transmission frequencies. These are mostly within the North American (902 to 928), Japanese (920-928 MHZ) and the European (863-876 MHz) frequency band. A list of supported Phys can be found in Table 4-1.

Table 4-1. Supported Phys

PHY ID	PHY Data Rate	Channel 0 Freq	# of Channels	Channel Spacing	Standard	TI-Setting Name
0	250 kbps	2405 MHz	16	5 MHz	Worldwide	IEEE802.15.4
1	50 kbps	902.2 MHz	129	200 kHz	FCC	IEEE802.15.4
3	50 kbps	863.125 MHz	64	200 kHz	ETSI	IEEE802.15.4
128	50 kbps	433.05 MHz	7	200 kHz	FCC/ETSI	IEEE802.15.4
129	5 kbps	902.2 MHz	129	200 kHz	FCC	Simple-Link Long Range
130	5 kbps	433.05 MHz	7	200 kHz	FCC	Simple-Link Long Range
131	5 kbps	863.125 MHz	64	200 kHz	ETSI	Simple-Link Long Range

Table 4-1. Supported Phys (continued)

PHY ID	PHY Data Rate	Channel 0 Freq	# of Channels	Channel Spacing	Standard	TI-Setting Name
132	200 kbps	902.4 MHz	64	400 kHz	FCC	IEEE802.15.4
133	200 kbps	863.225 MHz	32	400 kHz	ETSI	IEEE802.15.4
136	200 kbps	920.7 MHz	36	200 kHz	ARIB	IEEE802.15.4

4.2 15.4 Device Architecture

Simplelink devices can be used in different architectures. They can act as **stand-alone device**. In this architecture, the application and the protocol stack are running on the SimpleLink devices as single chip solution.

This reduces the cost of the system, but it is limited in performance and memory utilization metrics. The standalone architecture can be tested with the Sensor and Collector example provided in the Simplelink SDK.

An alternative architecture that can be used, is the **coprocessor** in which the Simplelink devices are used to run only the protocol stack. In this mode the NPI over a UART connection can be used to communicate to a dedicated application processor using the API-interface. A more detailed description of this interface can be found within the TI-15.4-Stack CoP Interface guide. The Coprocessor mode can be tested using the TI 15.4-Stack- Linux Gateway Project Zero example in the SimpleLink academy.

The difference between these architectures are shown in Figure 4-1.

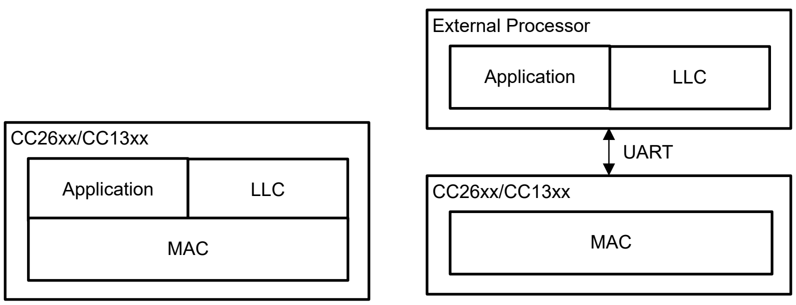

Figure 4-1. Differences Between These Architectures

4.3 15.4 Network Topology

The TI 15.4-Stack sets up a network in star topology, containing primarily two kind of devices. These two device types are defined within the IEEE802.15.4 standard.

The PAN-Coordinator is a central node, which creates a network and allows other devices to join. It is identified by the PAN-ID. The PAN-coordinator is usually the most power consuming device. Its task is to coordinate the network communication

However, when a device is joining the network, the PAN-coordinator sets its reporting interval to a desired value. The network structure is shown in Figure 4-2.

The collector example is a PAN-coordinator whereas the sensor example is acting as network device.

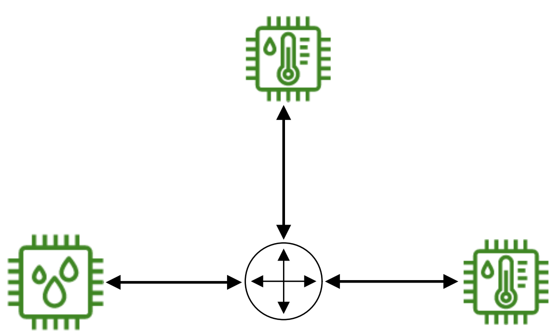

Figure 4-2. PAN Coordinator

The TI 15.4-Stack offers a lot of networking features, some other features like node balancing, extended network coverage and increased node count are not implemented on MAC and PHY layer. Those can be added on application layer.

Using the star network with a coordinator offers the possibility to run low-power sensors in a wireless network as it offers the opportunity to have sleepy nodes, which can turn off the radio during certain time periods.

4.3.1 Supported Network Modes

The TI-15.4 supports three operation modes: the Beacon Enabled, the Non-Beacon Enabled and the Frequency-Hopping mode. These modes are described in the CC13xx or CC26xx TI 15.4-Stack User's Guide.

4.3.2 Beacon-Enabled Mode

The Beacon-Enabled Mode is synchronized as the coordinator sends out beacons periodically. These beacons use the IEEE802.15.4 superframe structure. This network mode is recommended for applications where the data flow is mainly downstream (coordinator transmits to sensor nodes). The superframe consists of an inactive and an active period. This allows the PAN-Coordinator to go to sleeping mode in between beacons. Thus it is used whenever the PAN-Coordinator is running in an energy critical application. Since beacons can be used to specify which device has pending packets, not all nodes have to keep polling the Coordinator for data.

The Beacon-Enabled mode causes every sensor to wake up within the active period even if it does not have to transmit data. This increases the energy consumption of sensor devices. The active period duration has to be set as a trade off between power consumption and data-rate. The setup of the beacon mode causes a delay in packet transmission it is not possible to transit messages at any time..

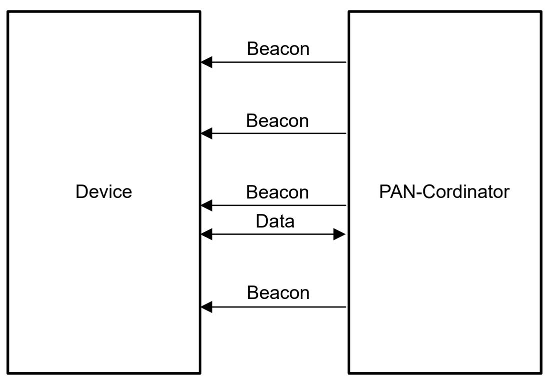

Figure 4-3. Beacon-Enabled Mode

If the device losses connection, it tries to resynchronize with the coordinator until it is able to track the beacon again. This is done by "listening" to its intended frequency.

Advantages:

- Super frame allows PAN-Coordinator to be inactive (sleep). This is not possible in Frequency hopping or Non-Beacon mode
- Synchronization and tracking provided
- Good if you can estimate your data transmission rate and know your system well

Disadvantages:

- Beacon causes every device to wake up and thus wastes power on devices which would not have to send data during a particular superframe
- Beacon leads to delay in transmission
- Devices might not be able to transmit or receive their required data within the active period
- If you do not know your network, there might be to many or to less active time

4.3.3 Non Beacon-Enabled Mode

In the Non-Beacon Enabled mode, the coordinator does not send periodic beacons, thus the network communication is not synchronous. The device is able to send frames to the coordinator that is always on. This allows the sensors to sleep most of the time and to optimize the power consumption of the network devices (sensor). The PAN-coordinator must always be awake, which increases its power consumption. This mode is not ideal for applications demanding low power consumption from the coordinator and a high data upstream from the sensor to the coordinator. The devices do not have to maintain connection, which consumes additional energy. This operation mode does not allow an inactive coordinator, thus it is not suitable for applications that aim for low power consumption on the coordinator.

Note that transfer is acknowledged by the coordinator. As soon as a device does not get a certain number of messages acknowledged it assumed that its orphaned by the Coordinator and sends out orphan notifications. A coordinator receiving an orphan notification starts a realignment. The coordinator itself does not notice if a device loses connection.

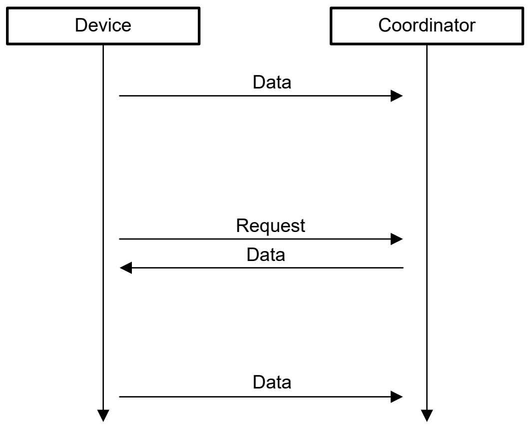

Figure 4-4. Non-Beacon Mode

Advantages:

- Low-power consumption on sensors
- No additional delay in messaging with 100% airtime

Disadvantages:

- High-power consumption on coordinator

4.3.4 Frequency Hopping Mode

TI implemented the Frequency Hopping mode based on the Wi-SUN frequency hopping. The Frequency hopping mode is made to allow a higher transmission power. The changing of frequency leads to less narrow band interferences and helps to create a system that is less likely to be intercepted or disturbed. The usage of multiple frequency bands also increases the robustness against jamming.

However, frequency hopping creates more complexity in a system. For more information on the frequency implementation, see the *CC13xx or CC26xx TI 15.4-Stack User's Guide*.

5 Security

The TI TI 15.4-Stack supports AES encryption as defined by IEEE802.15.4 specification. The application is responsible for key management, this is not done by TI 15.4-Stack initially. However, the application allows the developer to:

- Privacy
- Connect only trusted sources
- Avoid tracking

TI Simplelink devices include an AES accelerator, an ECC public key generator and a TRNG to support security measures. Several security enabled examples provided within the SDK.

Table 5-1. Security Commissioning Features Supported by TI 15.4 SDK Examples

Keys	**Device Key** **-Collector stores device key of every device** **Network Key (Predefined)** **-Known by every device**
Encryption-Layer	MAC-Layer Encryption
Decryption-Layer	MAC-Layer Decryption AES-CCM-MIC with 128-bit key
Key Storage	Keys stored in MAC layer
Key Exchange	ECDH P-256 (supported) Anonymous key agreement protocol
Key Derivation Algorithm	AES-CMAC and TRNG A shared secret is used to generate device key
Authentication	**Just Allow:** -no authentication -no MITM protection **Default Code:** -MITM-protection **Passkey:** -Collector: must be entered -Sensor: Displays authentication
Key Refreshment	TI provided API for key refreshment

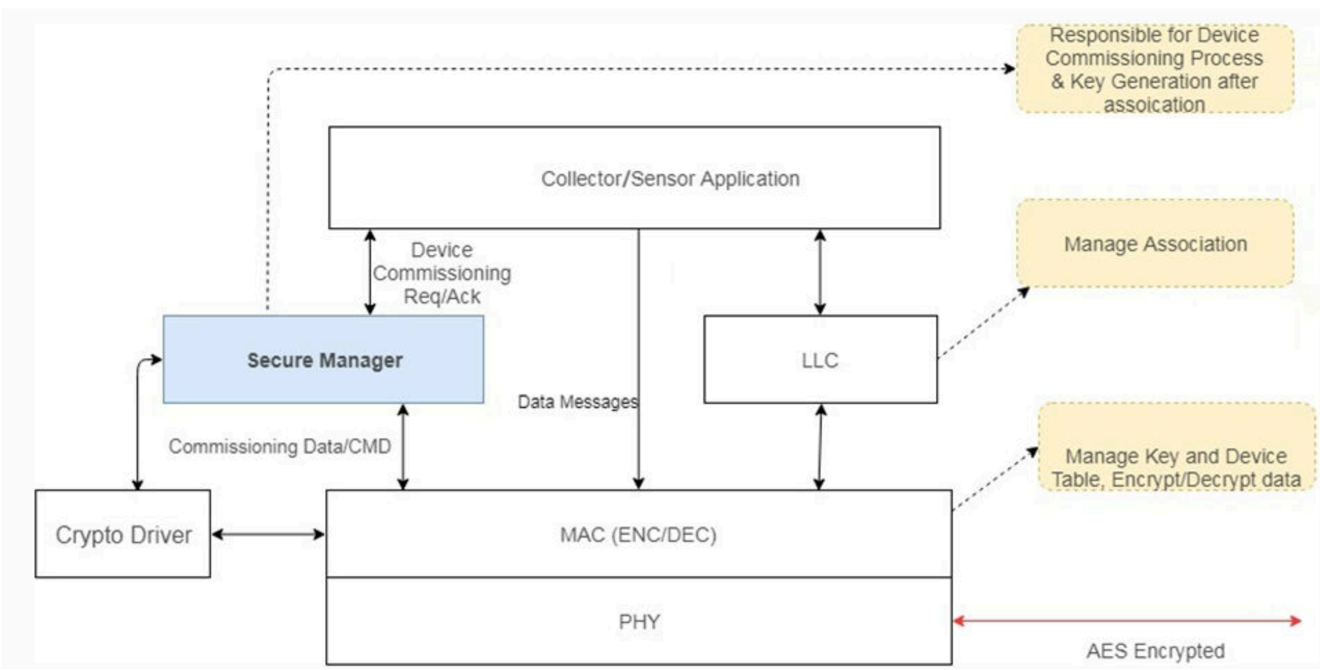

Figure 5-1. Security Implementation

6 Performance and Test Data

6.1 Test Data

6.2 Large Network Stability Tests

TI performed network stability tests for 15.4-star networks. Thus, we were able to prove the stability of our networks with up to 100 nodes. The tests are performed in a realistic, non-interference free area. The package error rate (PER) shows the percentage of messages that have not been transmitted correctly.

6.2.1 Sub1G

Band	Data Rate	Poll/Track/Report	No of Nodes	Mode	Avg PER
FCC	5 kbps	6s/400s/360s	75	BCN	0.03 %
FCC	5 kbps	400s/500s/400s	100	NBCN	0.02 %
FCC	50 Kbps	6s/40s/40s	75	FH	0.00%
FCC	50 kbps	6s/40s/40s	100	FH	0.08 %
ETSI	200 kbps	20s/100s/20s	100	NBCN	0.08 %

6.2.2 2.4 GHz

No of Nodes	Mode	Avg PER
75	BCN	0.00%
75	NBCN	0.01%

6.3 Transmission Rate

Due to the network setup, a 15.4 network never reaches 100 % of its possible data transmission rate. The possible datarate is affected by network setup, amount of nodes, interference as well as the used PHY and the reporting/polling structure of the network. Thus, it is not easy to predict the capabilities of a network without testing.

However, to get you an overview on possible capabilities some test data is shown in the following sections.

6.3.1 One Sensor Network

These measurements are done using one sensor with a report packet size of 100 Byte. Changing the payload size influences the possible data throughput.

In general, higher transmission rates will increase the PER.

Table 6-1. One Sensor Network

Mode	Data Rate	PER (%) [1]	Application Throughput (kbps)	Network Utility
NBCN	5 kbps	0.17%	3.26	80.11 %
NBCN	50 kbps	.312%	27.115	70.95 %
BCN	50 kbps	0.41%	25.39	66.5 %
FH	50 kbps	0.493%	21.94	69.65 %
NBCN	200 kbps	0.11%	81.5	-

1. Packet error rate (PER) - The number of packet failures as observed by the application which can be caused either due to channel access failure (channel being too busy to transmit the frame) or data ack failure (not receiving an acknowledgment from receiver even after maximum MAC retries).

6.3.2 Five Sensor Network

Table 6-2. Five Sensor Network

Mode	Datarate	Network Utility	PER (%)	Application Throughput (kbps)
NBCN Mode	50 kbps	43 %	4.418	15.598982
BCN Mode	50 kbps	43 %	1.048	16.148966
FH Mode	50 kbps	44 %	5.422	12.862608

1. Packet error rate (PER) - The number of packet failures as observed by the application which can be caused either due to channel access failure (channel being too busy to transmit the frame) or data ack failure (not receiving an acknowledgement from receiver even after maximum MAC retries).

6.3.3 47- Sensor Network

Table 6-3. 47- Sensor Network

Mode	Datarate	Network Utility	Delivery Ratio (%)	Application Throughput (kbps)
NBCN	5 kbps	35 %	87.8%	0.92
NBCN	50 kbps	45%	86.88%	7.84
BCN	50 kbps	40%	93 %	9.49
FH	50 kbps	55 %	97.03	9.38

7 Out-of-the Box-Experience

In order to speed up customers development process our SDK provides a set of out-of-box examples to give you some ideas of how to use several features of our 15.4 example. The examples can be found in TI-SimpleLink academy.

- The Sensor and Collector Project Zero examples give a insight on how to work with TI-15.4 stack and shows how to easily create a 15.4 based star topology network. It also helps to understand how different modes and their message exchange works.
- The Using TI-15.4 Stack and portable app example shows you an easy way, to port an application with our sensor-collector example.
- The Linux Gateway Projects Zero -gives an insight into how our devices work as co-Processor with a Linus application processor.
- Examples are also provided on how several security features in combination with our 15.4 example.
- With our Over the air download example provide some ideas on how to use 15.4 to run OAD updates on sensors. Our example contains the functions:
  - Determining if the image should be accepted
  - Receiving and unpacking image blocks
  - Writing and receiving the blocks to non volatile storage
  - Verifying the image post download

8 Tools

8.1 Code Composer Studio

Latest release of May 2023 is V12.3.0 Link to Code Composer Studio™ (CCS) is can be found on ti.com.

8.2 Sysconfig

A graphical user interface to configure our Simplelink devices. It is usable to configure pins, peripherals, radios and subsystems. It helps to create c-header and code files that can used as startup configuration of your custom design. It also allows you to adapt your system during your development process.

8.3 Packet Sniffer

Smart RF packet sniffer 2 is a toolbox to capture and display over-the-air packets.

8.4 Battery Life Calculator

The Battery Life calculator helps you to calculate the power consumption of your Simplelink-based TI-15.4-Stack application: TI 15.4-Stack Battery Life Calculator

These calculation can help you to before prototypes are available. The same thing can be done with our Launchpads and sensor/collector example. The Launchpads provides TI-Energy trace technology which to measure current consumption without additional equipment directly within your IDE.

8.5 Linux

The TI 15.4 Stack-Gateway-Linux Software Development Kit (SDK) provides a Linux software middleware for the TI 15.4 Stack companion solution. It includes a full Linux user-space software that runs on top of the TI Processor SDK for AM335x platform, which interfaces with the co-processor embedded implementation of TI 15.4 Stack running on the SimpleLink CC13xx wireless MCU.

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